Engine Heat Transfer

1. Impact of heat transfer on engine operation
2. Heat transfer environment
3. Energy flow in an engine
4. Engine heat transfer
   - Fundamentals
   - Spark-ignition engine heat transfer
   - Diesel engine heat transfer
5. Component temperature and heat flow

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Engine Heat Transfer

- Heat transfer is a parasitic process that contributes to a loss in fuel conversion efficiency
- The process is a "surface" effect
- Relative importance reduces with:
  - Larger engine displacement
  - Higher load

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Engine Heat Transfer: Impact

- **Efficiency and Power:** Heat transfer in the inlet decrease volumetric efficiency. In the cylinder, heat losses to the wall is a loss of availability.
- **Exhaust temperature**: Heat losses to exhaust influence the turbocharger performance. In- cylinder and exhaust system heat transfer has impact on catalyst light up.
- **Friction**: Heat transfer governs liner, piston/ ring, and oil temperatures. It also affects piston and bore distortion. All of these effects influence friction. Thermal loading determined fan, oil and water cooler capacities and pumping power.
- **Component design**: The operating temperatures of critical engine components affects their durability; e.g. via mechanical stress, lubricant behavior

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Engine Heat Transfer: Impact

- **Mixture preparation in SI engines:** Heat transfer to the fuel significantly affect fuel evaporation and cold start calibration
- **Cold start of diesel engines:** The compression ratio of diesel engines are often governed by cold start requirement
- **SI engine octane requirement:** Heat transfer influences inlet mixture temperature, chamber, cylinder head, liner, piston and valve temperatures, and therefore end-gas temperatures, which affect knock. Heat transfer also affects build up of in-cylinder deposit which affects knock.

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Engine heat transfer environment

- Gas temperature: ~300 – 3000°K
- Heat flux to wall: $\dot{Q}/A$ <0 (during intake) to 10 MW/m^2
- Materials limit:
  - Cast iron ~ 400°C
  - Aluminum ~ 300°C
  - Liner (oil film) ~200°C
- Hottest components
  - Spark plug > Exhaust valve > Piston crown > Head
  - Liner is relatively cool because of limited exposure to burned gas
- Source
  - Hot burned gas
  - Radiation from particles in diesel engines

Energy flow diagram for an IC engine

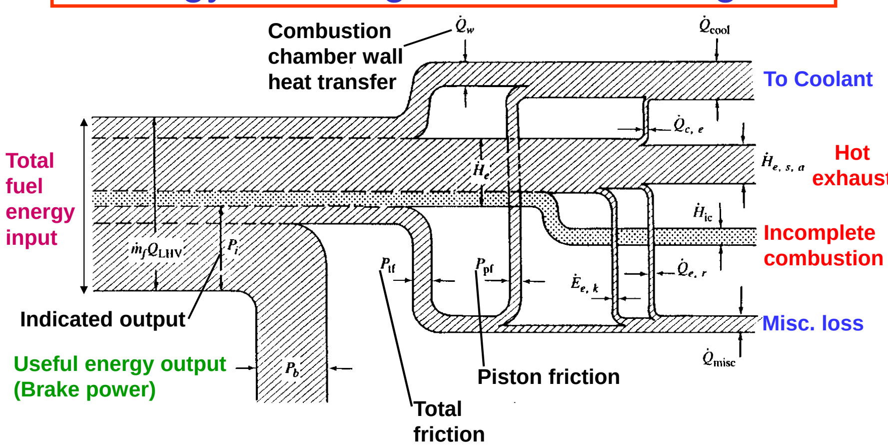

FIGURE 12-3
Energy flow diagram for IC engine. $(\dot{m}_f Q_{LHV})$ = fuel flow rate × lower heating value, $\dot{Q}_w$ = heat-transfer rate to combustion chamber wall, $\dot{H}_e$ = exhaust gas enthalpy flux, P_b = brake power, P_{tf} = total friction power, P_i = indicated power, P_{pf} = piston friction power, $\dot{Q}_{cool}$ = heat-rejection rate to coolant, $\dot{Q}_{c,e}$ = heat-transfer rate to coolant in exhaust ports, $\dot{H}_{e,s,a}$ = exhaust sensible enthalpy flux entering atmosphere, $\dot{H}_{e,ic}$ = exhaust chemical enthalpy flux due to incomplete combustion, $\dot{Q}_{e,r}$ = heat flux radiated from exhaust system, $\dot{E}_{e,k}$ = exhaust kinetic energy flux, $\dot{Q}_{misc}$ = sum of remaining energy fluxes and transfers.

Energy flow distribution for SI and Diesel

TABLE 12.1

Energy balance for automotive engines at maximum power

	P_b	$\dot{Q}_{cool}$	$\dot{Q}_{misc}$	$\dot{H}_{e,ic}$	$\dot{m}h_{e,s}$
	(percentage of fuel heating value)				
SI engine	25–28	17–26	3–10	2–5	34–45
Diesel	34–38	16–35	2–6	1–2	22–35

Sources: From Khovakh,[3] Sitkei,[4] and Burke *et al.*[5]

Update for modern engines:
SI engine in the low 30's
Diesel in the low 40's

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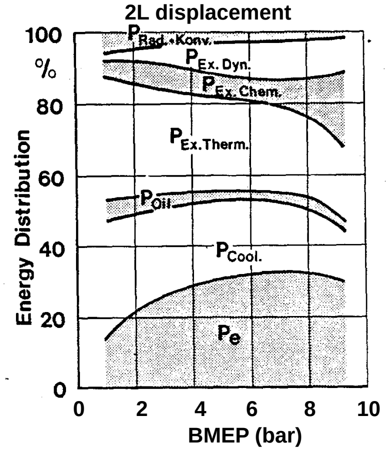
Energy distribution in SI engine

2000 rpm, water cooled SI engine 2L displacement



"Heat Balance of Modern Passenger Car SI Engines",Gruden, Kuper and Porsche, in *Heat and Mass Transfer in Gasoline and Diesel Engines*, ed. by Spalding and Afgan

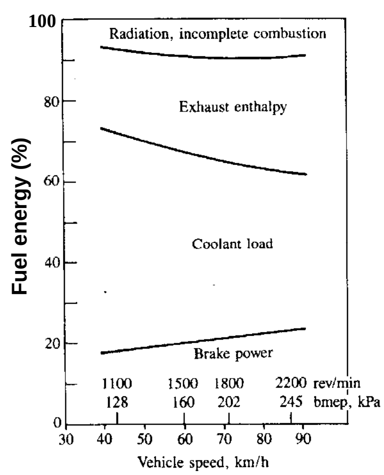


Fig. 12-4 SI engine energy distribution under road load condition, 6 cylinder engine; SAE Paper 770221, 1977

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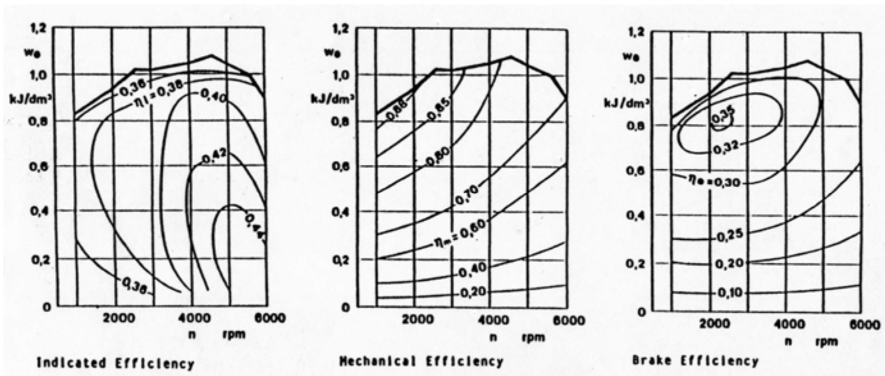
Efficiency of Passenger Car SI Engines



Source: D. Gruden, P.F., and F. Porsche AG. R & D Center Weissach, 1989.

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Heat transfer process in engines

- **Areas where heat transfer is important**
  - Intake system: manifold, port, valves
  - In-cylinder: cylinder head, piston, valves, liner
  - Exhaust system: valves, port, manifold, exhaust pipe
  - Coolant system: head, block, radiator
  - Oil system: head, piston, crank, oil cooler, sump
- **Information of interest**
  - Heat transfer per unit time (rate)
  - Heat transfer per cycle (often normalized by fuel heating value)
  - Variation with time and location of heat flux (heat transfer rate per unit area)

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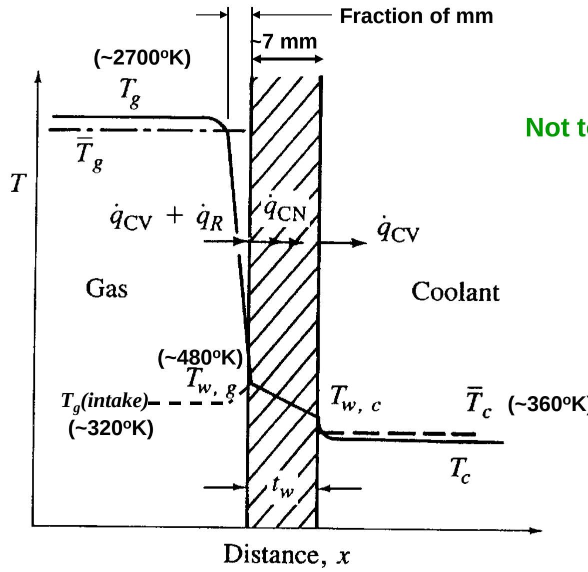
Schematic of temperature distribution and heat flow across the combustion chamber wall (Fig. 12-1)



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Combustion Chamber Heat Transfer

Turbulent convection: hot gas to wall

$$\dot{Q} = Ah_g(\bar{T}_g - T_{wg})$$

Conduction through wall

$$\dot{Q} = A\frac{\kappa}{t_w}(T_{wg} - T_{wc})$$

Turbulent convection: wall to coolant

$$\dot{Q} = Ah_c(T_{wc} - \bar{T}_c)$$

Overall heat transfer

$$\dot{Q} = Ah(\bar{T}_g - \bar{T}_c)$$

Overall thermal resistance: three resistance in series

$$\frac{1}{h} = \frac{1}{h_g} + \frac{t_w}{\kappa} + \frac{1}{h_c}$$

(κ_{alum} ~180 W/m-k
$\kappa_{cast\ iron}$ ~ 60 W/m-k
$\kappa_{stainless\ steel}$ ~18 W/m-k)

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Turbulent Convective Heat Transfer Correlation

Approach: Use Nusselt- Reynolds number correlations similar to those for turbulent pipe or flat plate flows.
e.g. In-cylinder:

$$Nu = \frac{hL}{\kappa} = a(Re)^{0.8}$$

h = Heat transfer coefficient
L = Characteristic length (e.g. bore)
Re= Reynolds number, $\rho UL/\mu$
U = Characteristic gas velocity
κ = Gas thermal conductivity
μ = Gas viscosity
ρ = Gas density
a = Turbulent pipe flow correlation coefficient

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Radiative Heat Transfer

- Important in diesels due to presence of hot radiating particles (particulate matters) in the flame
- Radiation from hot gas relatively small

$$\dot{Q}_{rad} = \varepsilon \cdot \sigma \cdot T^4_{particle}$$

σ = Stefan Boltzman Constant (5.67×10^{-8} W/m^2-K^4)
ε = Emissivity
where

$$T_{cyl.\ ave} < T_{particle} < T_{max\ burned\ gas}$$

- Radiation spectrum peaks at λ_{max}
  λ_{max} T = constant (λ_{max} = 3 μm at 1000K)

Typically, in diesels: $\overline{Q}_{rad} \approx 0.2\overline{Q}_{total}$ **(cycle cum)**

$\dot{Q}_{rad,max} \approx 0.4\dot{Q}_{total,max}$ **(peak value)**

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IC Engine heat transfer

- Heat transfer mostly from hot burned gas
  - That from unburned gas is relatively small
  - Flame geometry and charge motion/turbulence level affects heat transfer rate
- Order of Magnitude
  - SI engine peak heat flux ~ 1-3 MW/m^2
  - Diesel engine peak heat flux ~ 10 MW/m^2
- For SI engine at part load, a reduction in heat losses by 10% results in an improvement in fuel consumption by 3%
  - Effect substantially less at high load

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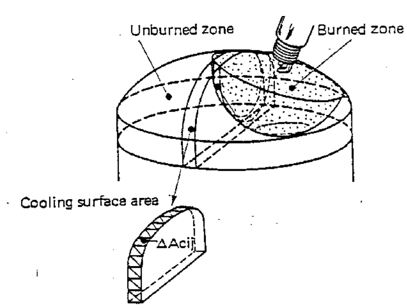
SI Engine Heat Transfer



- Heat transfer dominated by that from the hot burned gas
- Burned gas wetted area determine by cylinder/ flame geometry
- Gas motion (swirl/ tumble) affects heat transfer coefficient

Heat transfer

Burned zone: sum over area "wetted" by burned gas $\dot{Q}_b = \sum_i A_{ci,b} h_b (T_b - T_{w,i})$

Unburned zone: sum over area "wetted" by unburned gas $\dot{Q}_u = \sum_i A_{ci,u} h_u (T_u - T_{w,i})$

Note: Burned zone heat flux >> unburned zone heat flux

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SI engine heat transfer environment

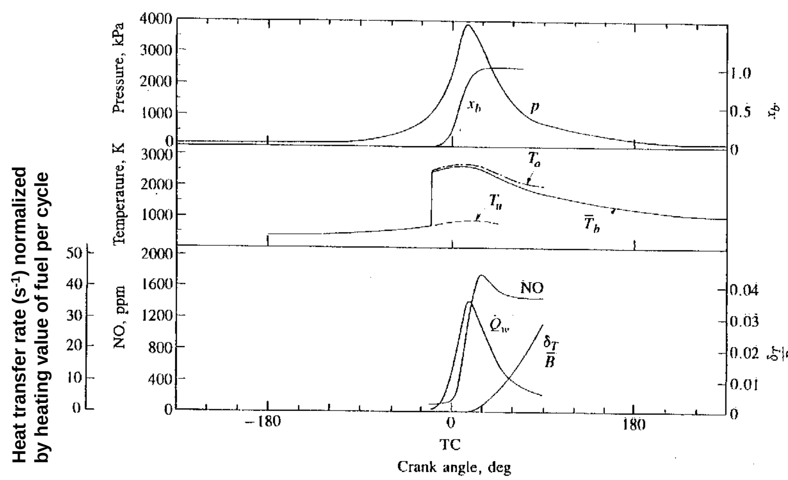

Fig. 14-9 5.7 L displacement, 8 cylinder engine at WOT, 2500 rpm; fuel equivalence ratio 1.1; GIMEP 918 kPa; specific fuel consumption 24 g/kW-hr.

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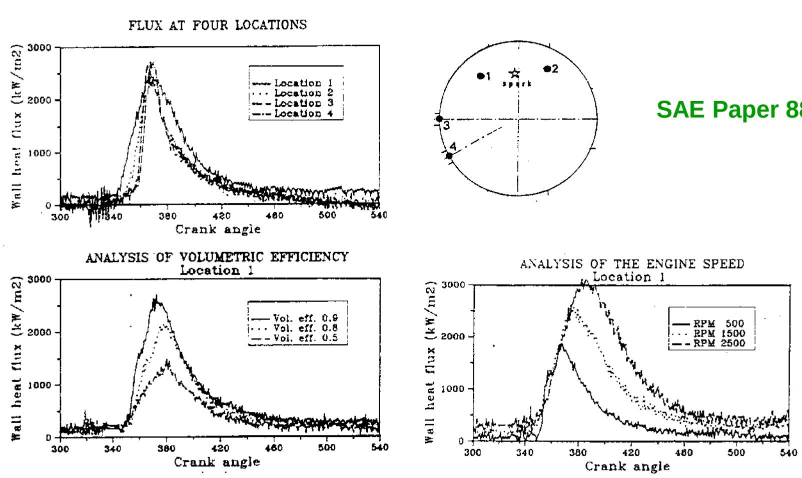
SI engine heat flux



SAE Paper 880516

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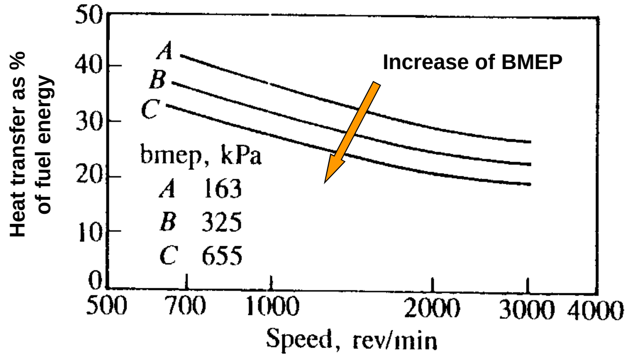
Heat transfer scaling



Nu correlation: heat transfer rate $\propto \rho^{0.8}N^{0.8}$

Time available (per cycle) $\propto 1/N$

Fuel energy $\propto \rho$

BMEP $\propto \rho$

Fig. 12-25

Thus Heat Transfer/Fuel energy $\propto BMEP^{-0.2}N^{-0.2}$

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Diesel engine heat transfer

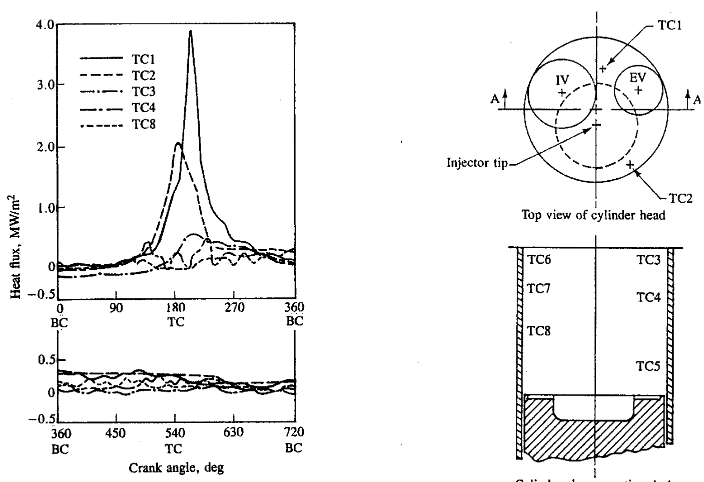

Fig. 12-13 Measured surface heat fluxes at different locations in cylinder head and liner of naturally aspirated 4-stroke DI diesel engine. Bore=stroke=114mm; 2000 rpm; overall fuel equivalence ratio = 0.45.

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Diesel engine radiative heat transfer

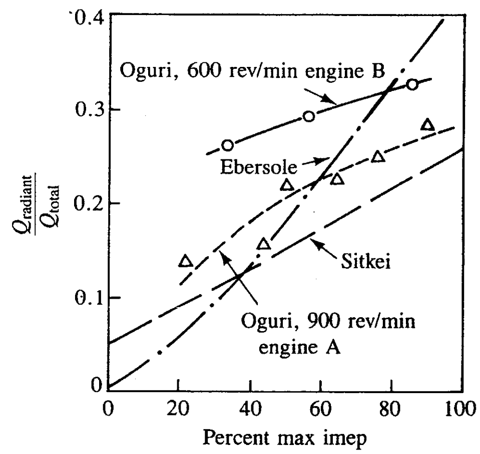

Fig. 12-15
Radiant heat flux as fraction of total heat flux over the load range of several different diesel engines

Heat transfer effect on component temperatures
Temperature distribution in head

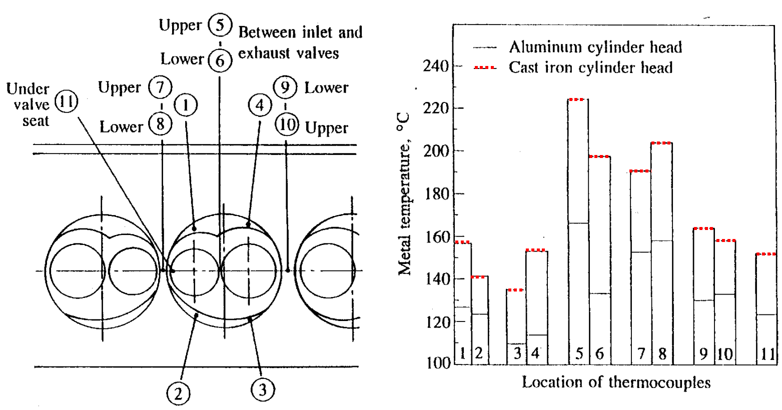

Fig. 12-20 Variation of cylinder head temperature with measurement location n SI engine operating at 2000 rpm, WOT, with coolant water at 95°C and 2 atmosphere.

Heat transfer paths from piston

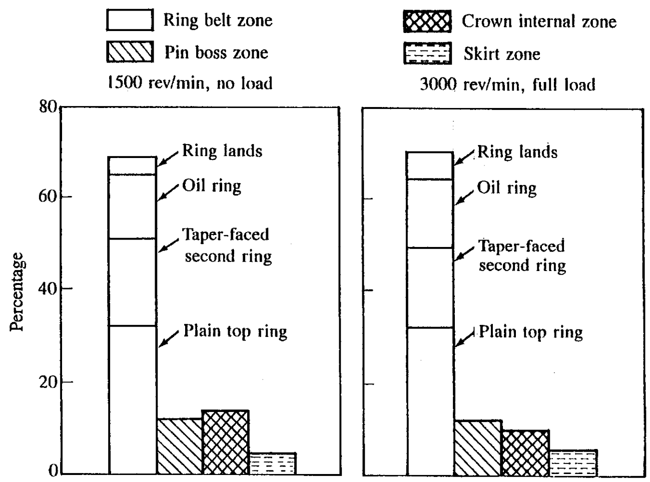

Fig. 12-4 Heat outflow form various zones of piston as percentage of heat flow in from combustion chamber. High-speed DI diesel engine, 125 mm bore, 110 mm stroke, CR=17

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Piston Temperature Distribution

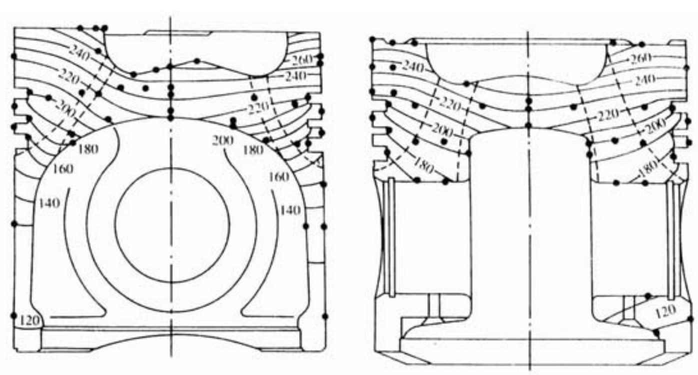

Figure 12-19

Isothermal contours (solid lines) and heat flow paths (dashed lines) determined from measured temperature distribution in piston of high speed DI diesel engine. Bore 125 mm, stroke 110 mm, r_c=17, 3000 rev/min, and full load

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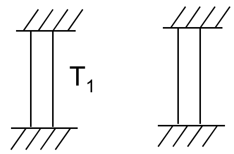
Thermal stress

Simple 1D example : column constrained at ends

Stress-strain relationship

$\varepsilon_x = [\sigma_x - \nu(\sigma_y + \sigma_z)]/E + \alpha(T_2 - T_1)$

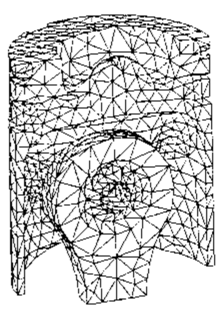


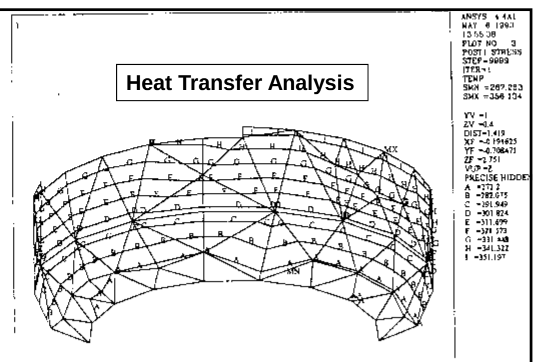
$T_2 > T_1$ induces compression stress

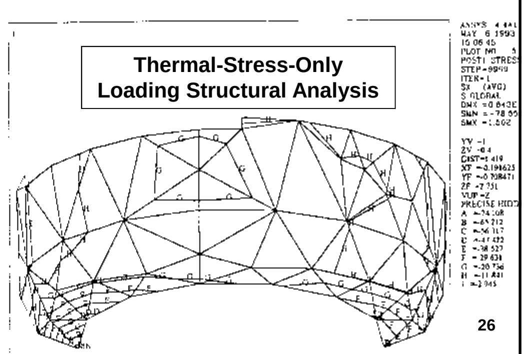
REAL APPLICATION - FINITE ELEMENT ANALYSIS

- Complicated 3D geometry
- Solution to heat flow to get temperature distribution
- Compatibility condition for each element

Example of Thermal Stress Analysis: Piston Design







Power Cylinder Design Variables and Their Effects on Piston Combustion Bowl Edge Stresses

J. Castleman, SAE 932491

Heat Transfer Summary

1. Magnitude of heat transfer from the burned gas much greater than in any phase of cycle
2. Heat transfer is a significant performance loss and affects engine operation
   - Loss of available energy
   - Volumetric efficiency loss
   - Effect on knock in SI engine
   - Effect on mixture preparation in SI engine cold start
   - Effect on diesel engine cold start
3. Convective heat transfer depends on gas temperature, heat transfer coefficient, which depends on charge motion, and transfer area, which depends on flame/combustion chamber geometry
4. Radiative heat transfer is smaller than convective one, and it is only significant in diesel engines

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